

*Water Resources Research*

Supporting Information for

**Hydropower production benefits more from 1.5°C than 2°C climate scenario**

Ying Meng1,2, Junguo Liu2, Sylvain Leduc3, Sennai Mesfun3,4, Florian Kraxner3, Ganquan Mao2,5, Wei Qi2 and Zifeng Wang2,6

1School of Environment, Harbin Institute of Technology, Harbin 150090, China, 2School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China, 3International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria, 4RISE Research Institute of Sweden (RISE), P.O Box 5604, 114 86, Stockholm, 5School of Water Resources and Hydropower Engineering, Wuhan University, Wuhan, 430072, China, 6Department of Geography, The University of Hong Kong, Hong Kong SAR, China

**Contents of this file**

Text S1 to S5

Figures S1 to S5

Tables S1to S3

**Introduction**

The supporting information provides additional description of the method and evaluation for the performances of the hydrological and power system model. The Text S1 presents Influence of RCP scenario selections on the results and evaluations of hydrological results. We add additional description of BeWhere model in the Text S2. The Text S3 presents evaluations of the BeWhere model results. The sensitivity of fossil fuel and transmission cost on potential hydropower production is shown in the Text S4. The Figure S1 presents the location of two hydrological stations (Lipat Kain and Kunyir) in Sumatra mainland. The Figure S2 and S3 show the hydrological model performance over the Sumatra. The Figure S4 shows the location of the existing dams in Sumatra, which was used to evaluate the performance or the power system model. The Figure S5 presents the sensitivity of fossil fuel on hydropower production. The Table S1 shows the comparison results of capacities between existing hydropower plants and simulated results.

Text S1

We used different representative concentration pathways (RCPs) and climate change scenarios to force the physically based hydrological modeling framework PCR-GLOBWB to quantify how global warming will affect hydropower potential in Sumatra. The uncertainties of PCR-GLOBWB, which are related to the parameters and meteorological forcing data, are discussed in detail by Weiland et al.(2015). The study showed that the parameter uncertainty comprises a relatively minor part of the hydrograph. Instead, the resolution of meteorological forcing data must be improved. To reduce uncertainties from meteorological forcing data, outputs of four GCMs (HadGEM2-ES, MIROC5, IPSL-CM5A-LR and GFDL-ESM2M) for both RCP2.6 and RCP6.0 were used because a large number of GCM outputs better represent the uncertainties in climate models(Tebaldi & Knutti, 2007).

We closely examined the hydrographs based on simulation results from PCR-GLOBWB and observation data from the Global Runoff Data Center (GRDC), which are representative of the dispersion between hydrological model performances and observation data. This procedure was performed for two different hydrological stations (Lipat Kain and Kunyir) in Sumatra (Figure S1), which featured discharge in different locations of Sumatra. Figure S2 displays the multiyear observed and simulated monthly discharges at the Lipat Kain and Kunyir stations. The trend of observed and simulated discharges is consistent, but the observed discharges are higher than the simulated discharges for peak times in several periods, with the exception of periods when observed data are missing. The correlation coefficients at Lipat Kain and Kunyir are 0.92 and 0.94, respectively (more validated metrics are provided in Table S1). Figure S3 presents the streamflow variability during the dry and wet seasons in Sumatra. The PCR-GLOBWB performs well for low flows in the dry and rainy seasons but it will underestimate the high flow significantly in the wet season at the Lipat Kain station. The simulated results could capture the trend of the discharge change.

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Figure S1. Locations of two hydrological stations (Lipat Kain and Kunyir) in Sumatra mainland.

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**Figure S2**. Multiyear observation and simulation by PCR-GLOBWB discharges, for a. the Lipat Kain station and b. the Kunyir station

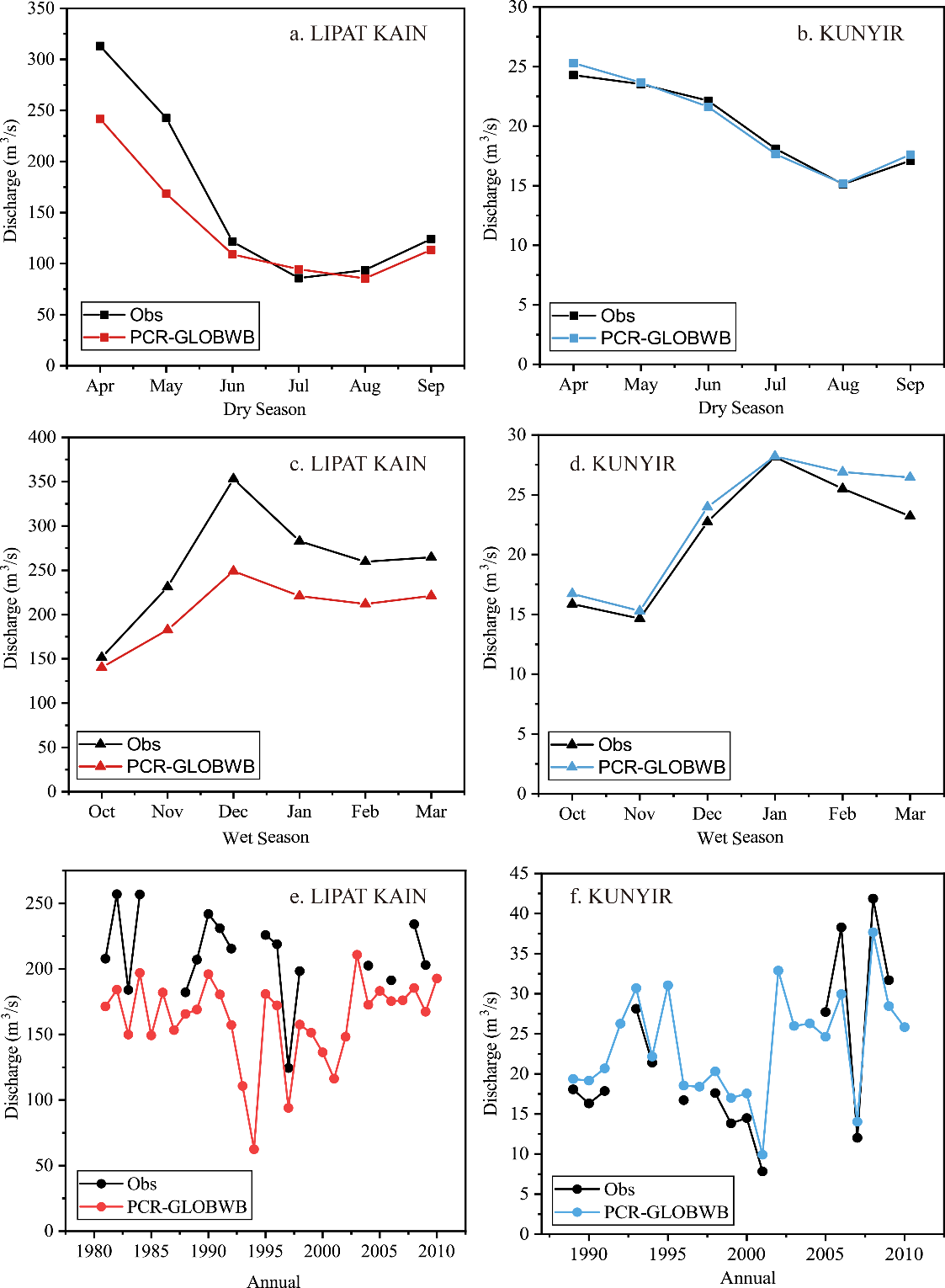


Figure S3. Streamflow variability during the dry season, wet season and annual bias, for the Lipat Kain station (a., c. and e.) and the Kunyir station (b., d., and f.)

Table S1. Evaluation of the hydrological model during the historical period using observed discharge.

| Performance metrics | Lipat Kain | | | Kunyir | | |
| --- | --- | --- | --- | --- | --- | --- |
| Dry Season | Wet Season | Annual | Dry Season | Wet Season | Annual |
| Mean Absolute Error (MAE) | 52.837 | 30.939 | 41.484 | 1.238 | 0.439 | 2.930 |
| Mean Bias Error (MBE) | -52.837 | -28.046 | -41.484 | 1.238 | 0.125 | 0.420 |
| Root Mean Square Error (RMSE) | 59.595 | 42.854 | 43.869 | 1.586 | 0.544 | 3.365 |
| Coefficient of determination (R2) | 0.950 | 0.970 | 0.816 | 0.962 | 0.980 | 0.933 |
| Index of agreement (D) | 0.728 | 0.944 | 0.651 | 0.975 | 0.994 | 0.957 |

Text S2

We assessed the sensitivity of discharge on the hydropower production under the historical period, RCP6.0-1.5°C and RCP6.0-2°C scenarios by varying the original discharge by ±50%, ±30% and ±10% to run the BeWhere model. Because we focus on the different effects under different global warming scenarios, we compared the difference in hydropower production under the historical period, RCP6.0-1.5°C and RCP6.0-2°C scenarios when the discharge varied (shown in Table 5). The change in hydropower production versus power demand ranged from -7.45% to 5.39, and the change in hydropower production versus power demand changed more when driven by power consumption (ranging from -7.45% to 5.39%) than power production sites (ranging from -0.05% to 2.70%). In addition, the maximum of the changes occurs when discharge decreases by 50% driven by power consumption from the historical period to RCP6.0-1.5°C. For global warming from 1.5°C to 2°C, the change in hydropower production versus power demand is less than 1% when driven by power production sites. Thus, although the hydropower potential has the highest sensitivity to discharge (Zhou et al., 2015), the hydropower production in our study has a low sensitivity to discharge alerting.

**Table S2.** The difference of hydropower production under the historical period and under the RCP2.6-1.5°C, RCP6.0-1.5°C and RCP6.0-2°C scenarios. (units: %).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Discharge variation | aRCP6.0-1.5°C - Historical period | | bRCP 6.0-2°C - Historical period | | cRCP 6.0-2°C - RCP 6.0-1.5°C | |
| Power Production Sites | Power Consumption | Power Production Sites | Power Consumption | Power Production Sites | Power Consumption |
| -50% | 2.74 | -3.54 | 2.64 | 0.12 | -0.10 | 3.66 |
| -30% | 0.05 | -1.21 | 0.07 | -0.92 | 0.03 | 0.28 |
| -10% | 0.05 | 0.61 | 0.02 | -1.06 | -0.03 | -1.67 |
| Original discharge | 0.03 | 3.91 | -0.05 | 2.19 | -0.08 | -1.72 |
| +10% | -0.08 | 1.06 | -0.02 | -0.28 | 0.05 | -1.34 |
| + 30% | -0.85 | 0.60 | 0.05 | -0.61 | 0.90 | -1.21 |
| +50% | -0.02 | -0.84 | 0.03 | -0.29 | 0.05 | 0.55 |
| d-50% - original discharge | 2.70 | -7.45 | 2.69 | -2.07 | -0.02 | 5.39 |
| d-30% - original discharge | 0.01 | -5.12 | 0.12 | -3.12 | 0.11 | 2.00 |
| d-10% - original discharge | 0.02 | -3.30 | 0.07 | -3.26 | 0.06 | 0.05 |
| d+10% - original discharge | -0.11 | -2.85 | 0.03 | -2.47 | 0.14 | 0.38 |
| d+30% - original discharge | -0.88 | -3.31 | 0.10 | -2.80 | 0.99 | 0.51 |
| d +50% - original discharge | -0.05 | -4.76 | 0.08 | -2.48 | 0.13 | 2.27 |
| athe difference between RCP6.0-1.5°C and Historical period; bthe difference between RCP6.0-1.5°C and Historical period;cthe difference between RCP6.0-2°C and RCP6.0-1.5°C; dthe difference between discharge variation and original discharge. | | | | | | |

Text S3

The BeWhere model is a techno-economic engineering model used to identify the optimal locations for hydropower plants under different levels of global warming (Leduc et al., 2010; Sylvain Leduc, 2009; Mesfun et al., 2017).

The overall objective of the model is to minimize the entire cost (*Ctot*) of the energy supply chain according to the following:

(1)

where *Csupply chain* is the supply chain cost (variable), *Esupply chain* is the supply emissions (variable), and *CCO2* is the cost of emitting *CO2* (parameter). The supply chain cost *Csupply chain* in turn accounts for:

(2)

where Csupply chain is the supply chain cost, *Cset up* is the cost of setting up new hydropower plants, and *CO&M* is the cost for operation and maintenance. CT is the cost of transmission and *Cfossil fuel* is cost for competing against fossil fuel.

The transmission cost (*CT*) is defined as follows:

(3)

where *Pnew plants* is the amount of power produced from the hydro station (variable), *D* is the transmission distance from hydropower plants to power consumption points (variable) and *α* is a parameter related to the cost of connecting transmission lines.

The transmission cost represents the total cost of constructing transmission lines connecting new hydropower plants to an existing power transmission hub. A connecting transmission line cost of 1 $/km-kW is used assuming an economic lifetime of 40 years (Mesfun et al., 2018). The distance between the potential hydropower plant sites and the nearest hub is calculated by a network map of hub routes, which is parameterized in the model for cost estimation. This method has been described in detail by Leduc (2009).

The total cost of fossil fuel is the price of fossil fuel (parameter), which is 0.113 $/kWh in Indonesia, multiplied by the amount of fossil fuel-based electricity, which is a variable.

The supply chain emissions *Esupply chain* includes the emissions of fossil CO2 from fossil-based power. *Esupply chain* is the emission factor (parameter) multiplied by the amount of fossil fuel (variable) used. The cost of emitting CO2 (CCO2) varies greatly among countries (Mesfun et al., 2017), and our simulation used 10 $/t CO2 (Timilsina et al., 2011).

Text S4

We ran the historical period hydropower plant distribution and summarized the hydropower potential at the current existing hydropower plant sites in Sumatra. We found that the simulated plant capacities provided by the BeWhere model were higher than the installed capacities of the exiting hydropower plants. Our simulated results are the potential hydropower capacities, not the actual installed capacities. The development of micro- and mini- hydropower plants is popular in Indonesia because large-scale power plants are not safe to build due to environmental issues, such as the safety of fish (Hasan et al., 2012). As for simulation result is very close to the installed capacity at the site of Koto Panjang Kampar, it’s because the power demand at Koto Panjang Kampar site is relatively higher than the surrounding area (shown in Figure S4), which cause it is necessary to develop adequately the hydropower resource. On the other hand, the BeWhere model simulated results followed the results from the PCR-GLOWBW. While as we mentioned in Text S1, the PCR-GLOWBW model underestimated the discharge (shown in Figure S2), which would cause the underestimation of the hydropower potential capacity in chain.

Table S3. Comparison of capacities between existing hydropower plants and simulated results.

| Existing hydropower plants | | | | Simulated potential capacity (MW) |
| --- | --- | --- | --- | --- |
| Name | Latitude | Longitude | Installed capacity (MW) |
| Asahan I | 2.51 | 99.26 | 180.00 | 1542.66 |
| Sigura gura (asahan II) | 2.52 | 99.28 | 286.00 | 1542.66 |
| Tangga (asahan II) | 2.55 | 99.30 | 317.00 | 1542.66 |
| Koto Panjang Kampar | 0.29 | 100.88 | 114.00 | 114.38 |
| Lau Renun | 3.08 | 98.07 | 82.00 | 239.85 |
| Maninjau III | -0.29 | 100.15 | 123.00 | 560.50 |
| Musi | -3.77 | 102.44 | 215.48 | 1176.71 |
| Singkarak | -0.69 | 100.60 | 175.00 | 356.08 |
| Sipansihaporas | 1.74 | 98.78 | 50.00 | 146.38 |

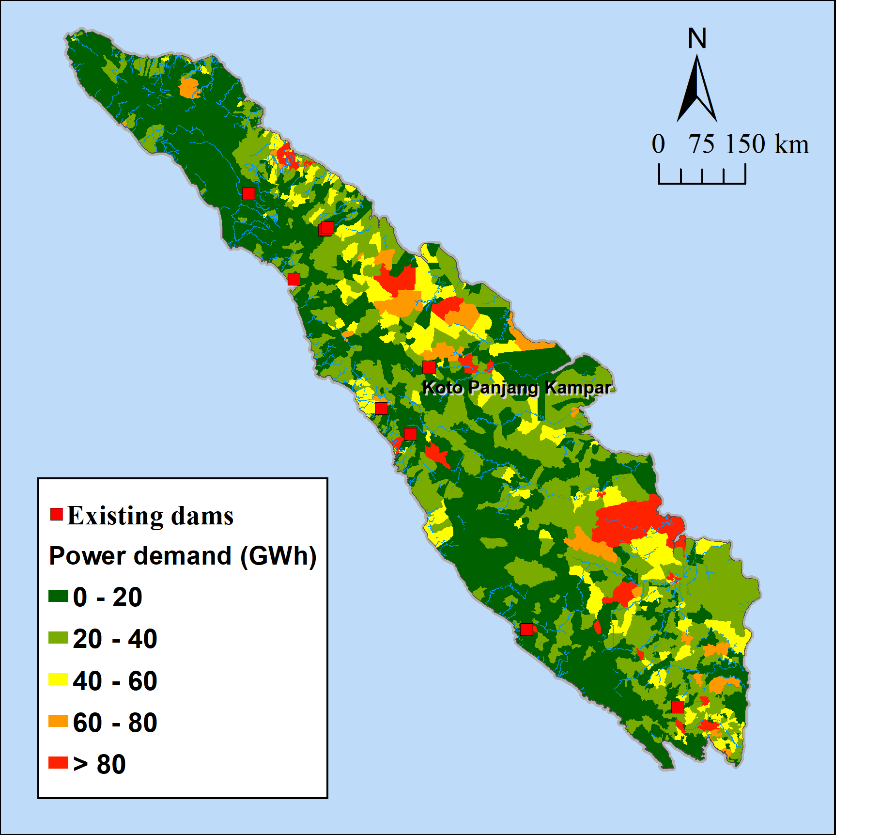
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Figure S4. The Location of the existing dams in Sumatra

Text S5

We evaluated the sensitivity of fossil fuel cost on our results to determine the sensitivity of our results to fuel volatility (shown in Figure S4). We adjusted the fossil fuel cost from 0 to 0.25$/kWh, and the fossil fuel cost range is generally approximately 0.05-0.175$/kWh(IRENA, 2019). The sensitivity results presented that the effects of fossil fuel cost on our results are moderate among the fossil fuel cost range. This result is because the actual hydropower generation could be influenced notably by fossil fuel volatility (Mesfun et al., 2017). However, in our study, we mainly assessed the potential hydropower production, rather than the actual hydropower production. Therefore, our results are not sensitive to fossil fuel volatility.

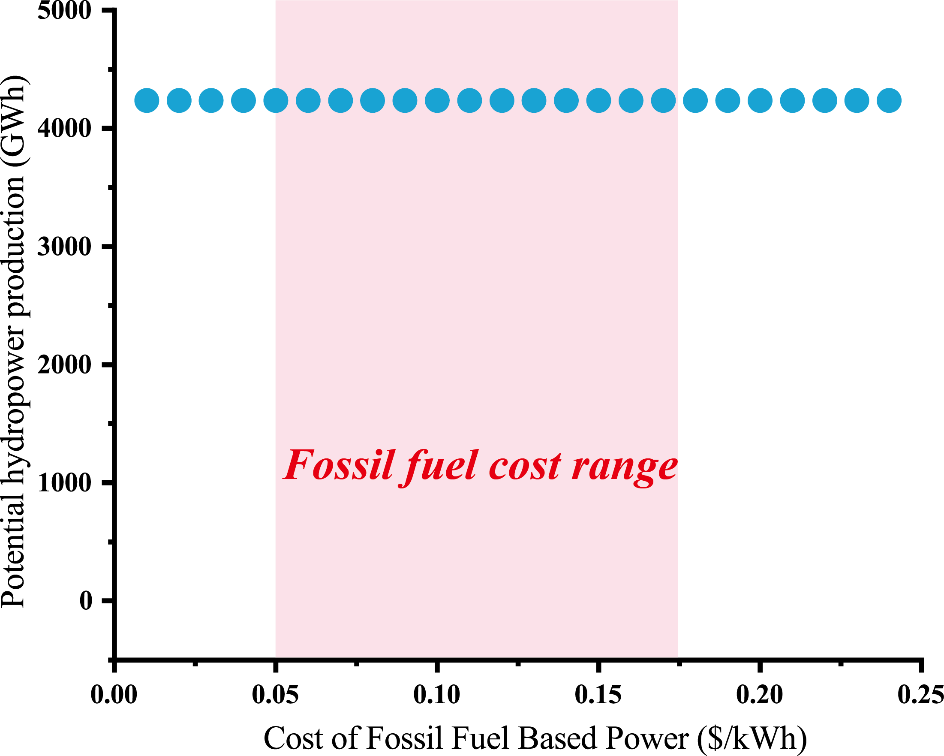


Figure S5. Sensitivity of fossil fuel on hydropower production

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